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NEURAL ACTIVATION DURING DIMENSIONAL LABEL LEARNING PREDICTS DIMENSIONAL ATTENTION

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I am submitting herewith a thesis written by Hollis Heim entitled "NEURAL ACTIVATION DURING DIMENSIONAL LABEL LEARNING PREDICTS DIMENSIONAL ATTENTION." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Experimental Psychology.

Dr. Aaron Buss, Major Professor

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

**NEURAL ACTIVATION DURING DIMENSIONAL LABEL LEARNING
PREDICTS DIMENSIONAL ATTENTION**

A Thesis Presented for the
Master of Arts
Degree
The University of Tennessee, Knoxville

Hollis Lee Ratliff Heim

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ABSTRACT

Previous research suggests that children's ability to label visual features (e.g., "red") and dimensions (e.g., "color") can change aspects of their attention to visual dimensions (Buss & Kerr-German, 2019). Based on this research, the goal of this study is to investigate whether children's dimensional attention can be predicted by the neural dynamics of dimensional label learning (DLL). We used functional near-infrared spectroscopy (fNIRS) to measure hemodynamic changes in left frontal, left parietal and left temporal cortices previously implicated in dimensional attention (Morton et al., 2009; Buss & Spencer, 2018) while participants completed a battery of dimensional label learning and dimensional attention tasks. Dimensional attention was measured using the dimensional change card sort task (DCCS) which measures explicit flexible dimensional attention, a dimensional attention priming task which measures implicit attentional stability, a matching task which measures selective attention and property-property mapping, and the triad classification (TC) task which measures children's implicit selective attention. It was found that the temporal cortex was activated during the DLL tasks. Further, it was found that successful performance on the dimensional attention tasks was associated with activation in the parietal cortex for the DLL tasks. On the other hand, low performance on the dimensional attention task was marked with activation in the temporal cortex and ventrolateral prefrontal cortex for the DLL tasks.

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CHAPTER 1: INTRODUCTION

Attention is a critical aspect of cognition that encompasses a set of skills utilized to select information to be process, enhance task-relevant information to be processed, or guide cognitive processing in a goal-directed fashion. The current study focuses on an element of attention: attention to visual dimensions. Specifically, the allocation of processing resources between different visual dimensions such as color and shape. This form of attention, known as *dimensional attention*, is important when dimensions of stimuli are relevant to the task, such as shapes and colors. Dimensional attention can be examined implicitly through similarity-based attentional guidance or explicitly through rule-based tasks.

One aspect of dimensional attention is *selective attention*, which encompasses the ability to focus processing on specific visual information such as features of an object. In other words, the ability to focus attention on specific features of an object (e.g., attending to the redness of a red apple). Another form of dimensional attention is *attentional stability*, which is the ability to sustain attention. Both selective attention and attentional stability relate to one another in that to successfully sustain attention requires the ability to focus attention on specific features. Another form of dimensional attention is *flexible attention*, which is the ability to flexibly shift attention between dimensions. Both selective and flexible attention relate to one another because to successfully shift attention between dimensions, attention to the specific features of an object needs to be accomplished.

One commonly used measure of explicit rule-based dimensional attention over development is the Dimensional Change Card Sort (DCCS) task (Zelazo, 2006). In this task, children are asked to sort cards by either color or shape and then to switch and sort by the other dimension. Typically, 3-year-olds perseverate and continue to sort by the first set of rules even when told to switch to the second set of rules whereas most 4-year-olds easily switch rules (Buss & Spencer, 2014). The DCCS task involves multiple types of attention including flexible attention and aspects of selective attention (Hanania & Smith, 2010). That is, children must be able to both ignore the features of the irrelevant dimension and to shift attention to focus on features across dimensions as the rules of the task change. Indeed, previous research has shown that measures of attention in the DCCS task are related to performance on tasks that measure implicit attentional stability and selectivity (Buss & Kerr-German, 2019; Benitez et al., 2017). Children who successfully switched on the DCCS task were more likely to sustain their attention in an implicit attentional stability task when compared to children who perseverated in the DCCS task (Benitez et al., 2017). Moreover, children who successfully switched attention also demonstrated higher levels of attentional selectivity in an implicit selective attention task (Buss & Kerr-German, 2019). These results indicate the interconnectedness of flexible attention and attentional stability.

These lines of research situate attention in the context of visual dimensions of objects. One central process that has been implicated in how children use attention is their level of ability in labelling features of an object (Buss & Spencer, 2014). Specifically, the ability to understand labels for objects and object features (e.g., shape or

color) may have an impact on dimensional attention. Vales and Smith (2015) found that knowledge of labels (e.g., “red” or “circle”) facilitated 3-year-olds’ ability to select the target in a visual search task. This finding suggests that there may be a connection between memory association of dimensional labels and attention. Specifically, strong memory representations of color and shape labels may impact their ability to switch attention between dimensions. Further, the frequency that shape and color labels are spoken in a child’s environment also appears to impact children’s ability to use labels to guide attention (Buss & Nikam, 2019). Thus, to understand how learning labels impacts dimensional attention, the current study sought to investigate the neural dynamics of dimensional label learning and how that predicts performance in explicit and implicit dimensional attention tasks.

CHAPTER 2: THE ROLE OF DIMENSIONAL ATTENTION

Flexible Attention

Flexible attention encompasses the ability to flexibly shift attention between dimensions. The DCCS is one task that is commonly used to measure explicit rule-based flexible attention development, most often in 3- and 4-year-olds. In this task, the participant disengages from sorting by one dimension and then engages in sorting by the other dimension. As mentioned above, younger children tend to perseverate and continue to sort by the pre-switch dimension while older children have no trouble with switching between dimensions when instructed. Many theoretical debates have focused on explaining the developmental shift in performance between 3- and 4-year-olds in the DCCS. It has been suggested that younger children fail to flexibly shift attention in the post switch phase because children's attention is stuck on the pre-switch dimension due to "attentional inertia" (Kirkham et al., 2003; Rennie et al., 2004). However, the attentional inertia hypothesis does not allow for environmental factors like label learning and instead focuses on maturational effects. This results in a theory which does not offer an explanation to the neurological processes behind successful DCCS performance besides pure maturation. Another theory suggests that flexibility in the DCCS develops due to strengthening the active representations of the rules in the task (Chatham et al., 2012; Morton & Munakata, 2002; Yerys & Munakata, 2006). This theory, known as the Connectionist Model, offers a partial explanation of the potential neural mechanisms behind DCCS performance but does not generalize to all forms of the DCCS (Buss & Spencer, 2014). This could be because the Connectionist Model focuses on the prefrontal

cortex while other models show that the posterior regions are important as well in the DCCS (Buss & Spencer, 2018; Morton & Munakata, 2002). Further, the cognitive complexity and control (CCC) theory suggests that children's limited ability to shift attention in the DCCS is due to a failure to reflect on the specific rules of the task (Zelazo et al., 2003). The CCC theory has very good generalizability to performance in different versions of the DCCS, however it does not explain how children learn to reflect on the rules of the task and does not attempt to integrate neural mechanisms into the theory.

To address these limitations, and to explore the processes underlying dimensional attention, Buss and Spencer (2014) presented a dynamic neural field (DNF) model to address the developmental shift of DCCS performance in children (see Figure 1). The model simulates real-time neural dynamics to understand the mechanisms involved in the DCCS task. In this model, the ability to shift sorting rules is based on object representations that bind the visual features of an object (e.g., red or circle) to a spatial location (e.g., left or right). These object representations are bound to a system of representations of dimensional labels (e.g., "shape" and "color"). By activating a label representation such as, "shape", the ability to process shape features becomes enhanced. This allows for the correct choice to be selected despite the conflict in the task. In the pre-switch phase, a memory trace forms from sorting by the pre-switch dimension that carries into the post-switch phase, causing additional conflict. Therefore, if the relationship between dimensional label representation and object representation is weak, the model will continue to sort by the pre-switch dimension in the post-switch phase. When the association between dimensional label representation and object representation

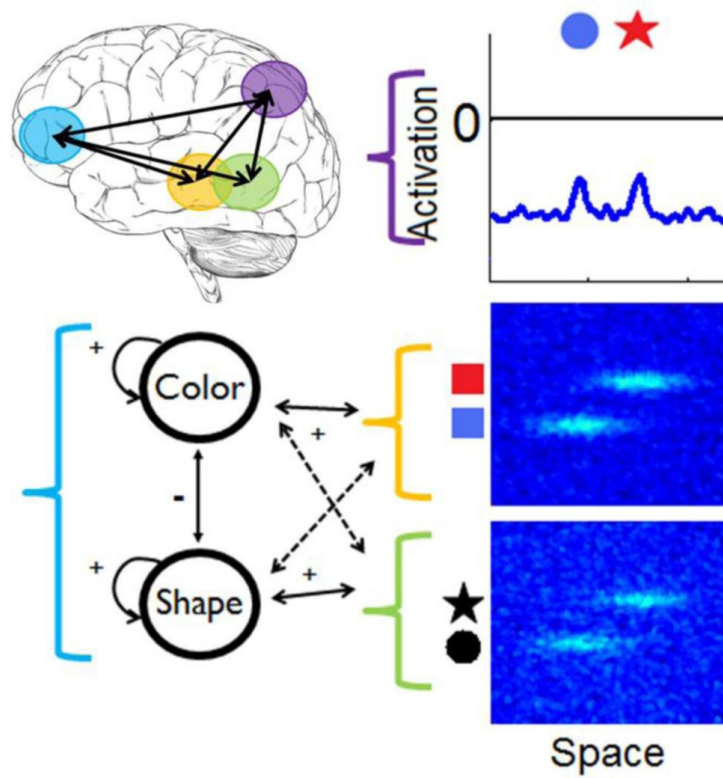


Figure 1. The DNF model created by Buss & Spencer (2014). The ability to shift sorting rules is based on object representations that binds the visual features of an object (e.g., red or circle) to a spatial location (e.g., left or right). This object representation is bound to a system of representations of dimensional labels (e.g., “shape” and “color”)

strengthens, the model overcomes the memory trace bias built up in the pre-switch phase and successfully switches during the post switch phase. This model shows that the developmental shift in the DCCS can be explained by strengthening associations between dimensional labels and visual features.

Attentional Stability

Attentional stability refers to the ability to sustain attention. This function of attention has been studied using an implicit attentional stability task known as the dimensional priming (DP) task (Medin, 1973). In this task, children are first shown a reference object (e.g., a blue triangle) and two choice objects (e.g., a blue square and a red circle). Then, children are asked to pick the choice object that goes best with the reference object. The first two trials are priming trials, such that there is only one matching option among the choices (e.g., color). After the priming trials, children are administered a series of test trials which consist of a reference object (e.g., a blue triangle) and two choice objects that match the reference object along different dimensions (e.g., a blue square and a red triangle). Children are asked to pick the choice that goes best with the reference object. Older children are more likely to continue selecting the primed dimension compared to younger children (Medin, 1973). This suggests that children can be primed to sort by one dimension and sustain their attention without explicit instruction.

Benitez et al. (2017) explored the connections between sustained attention using the DP task, and flexible attention using the DCCS. They found that children who successfully switched in the DCCS task were more likely to sustain their attention in the

DP task when compared to children who perseverated in the DCCS (Benitez et al., 2017). This finding is interesting because it would initially seem that attentional stability would cause a participant to perseverate in the DCCS. Benitez et al. (2017) suggests that potentially, children who perseverate in the DCCS have less stable attention and therefore distribute their attention to both dimensions during the task. On the other hand, children who successfully switch in the DCCS are more able to stabilize their attention selective dimensions, which aids in the DP task (Benitez et al., 2017). This finding further shows the way selective attention can aid in attentional stability and flexible attention. On the other hand, children who successfully switch in the DCCS can stabilize their attention to one dimension and therefore can be successfully primed in the DP task.

Selective Attention

Selective attention refers to the ability to focus processing on specific visual information such as features of an object. The main task that measures implicit selective attention is the triad classification (TC) task (Smith & Kemler, 1977). In this task, children are shown a reference object and two choice objects and told to pick the choice object that goes best with the reference object. One of the choice objects is maximally different from the reference object along one dimension, but exactly the same as the reference object along the other dimensions. This object is referred to as the identity (ID) choice. The other object does not match exactly to the reference object but is overall more similar to the reference object along both dimensions combined. This object is referred to as the holistic (H) choice. The holistic choice is a better option when looking at the information across both dimensions, but the identity choice is a better option when

information is considered selectively along one dimension. Previous studies have found that younger children tend to select the holistic choice and older children tend to select the identity choice (Smith & Kelmer, 1977). This suggests that as children develop, they are better able to selectively attend to specific dimensions.

The TC task encompasses aspects of flexible attention as well. In the task, the identity object is randomized throughout the trial such that the relevant dimension can randomly change between shape and color over trials. The instructions are implicit, but there is an element of flexible attention where children need to shift their attention from selectively attending to shape or color. Previous research has shown that children who perseverated in the DCCS task performed more poorly in the TC task when two repetitions preceded a dimension shift compared to when only a single repetition preceded a dimensional shift (Buss & Kerr-German, 2019). Hanania and Smith (2010) explored the relationship between the TC and DCCS and found that perseverance in the DCCS is directly influenced by the children's immaturity of selective attention. Previous research found that selectivity and flexibility of attention influence one other. For example, it has been shown that decreasing selective attention load in the DCCS improves performance (Diamond et al., 2005; Kloo & Perner, 2005). Further, increasing selective attention demands decreases performance in younger children in the DCCS (Fisher, 2011). These studies further the idea that there are common processes in different aspects of dimensional attention.

CHAPTER 3: DIMENSIONAL LABEL LEARNING

Previous research has found that mastering dimensional labels such as, “color” involves more than associating a label to an object, but instead involves a system of mappings (Sandhofer & Smith, 1999). First, children must understand word-word mappings such that “color” is associated with labels of color such as, “green” and, “red”. Next, children learn word-property mappings which link words (e.g., red) to the colors of the object (e.g., the redness of a red flower). Further, children learn property-property mappings which accompany the concept of relating multiple objects by a similar dimensional feature. For example, understanding that a red cup, a red ball, and a red flower are similar in their redness. Lastly, children learn word-word-property mapping which links the question, “What color is this?” to the label, “red” and the redness of an object (e.g., red flower).

Sandhofer and Smith (1999) developed a set of tasks to measure the system of mappings involved with label learning and sought out to find the order in which these color mappings develop. In this study, toddlers performed three color label learning tasks: production, comprehension, and matching. In the production task, children were asked, “What color is this?”. If the child answers the experimenter by saying a color, this exemplifies word-word mapping. Further, when children answer correctly, this task shows proper understanding of property-word mappings, successfully linking a feature of an object to the label, “red”. In the comprehension task, children were shown an array of objects of different colors and told to, “Show me the red one”. When children respond correctly, this task measures successful word-property mapping, linking the label, “red”

to features of the object. In the matching task, children were shown one or two exemplar objects, and then shown six choice objects. Children were then asked to find the object that matched the exemplar object(s). Correct responses to the matching task exemplify property-property mapping, successfully relating multiple objects by a similar dimensional feature. It was found that children learn word-word mappings first, followed by word-property mapping and then eventually combine those two skills to perform property-property mapping (Sandhofer & Smith, 1999). Interestingly, while it may seem to be that children would be able to abstract the color of objects before learning the labels for colors, the matching task testing for property-property mapping seems to be the most difficult. Sandhofer and Smith (1999) proposed that the reason for this is that the difficulty in the matching task involves selective attention. Children must learn a series of color labels which guide their attention to the dimension of color in the object, allowing them to correctly match colors.

Dimensional Label Learning as a Developmental Mechanism

The dynamic neural field model proposed by Buss & Spencer (2014) suggests that label representations enhance cognitive processing of task-relevant visual features in the DCCS. Specifically, when children learn labels for visual features, a structure of connectivity between the frontal and posterior regions of the brain are formed. Neural activation of labels, such as, “shape” and, “color” enhances the processing of task-relevant dimensions. Features and labels are coupled reciprocally such that features can result in the activation of labels, and labels can result in the activation of features.

Therefore, dimensional label knowledge may play a role in the developmental shift in dimensional attention.

Previous research has found that providing dimensional labels during the DCCS can support switching (Doebel & Zelazo, 2013). Further, it has been shown that children are better able to switch rules in the DCCS if they were given general uninformative labels during the pre-switch phase, but informative labels during the post-switch phase (Yerysm & Munakata, 2006). A study done by Lowery, Kerr-German, and Buss (2018) explored the relationship between the Dimensional Label Learning (DLL) tasks and the DCCS task using fNIRS. In this experiment, 3- and 4- year-olds were given all of the DLL tasks administered by Sandhofer and Smith (1999) as well as the DCCS to explore the role of dimensional label learning in the development of flexible attention. It was found that color label production produced frontal and temporal cortex activation that predicted performance in the DCCS (Lowery et al., 2018). These results suggest that these neural systems associated with the DLL tasks influence children's ability to flexibly attend in the DCCS.

CHAPTER 4: THE CURRENT STUDY

The current study sought to investigate the relationship between the neural dynamics and performance of dimensional label learning and explicit and implicit aspects dimensional attention. This is one of the first studies exploring the neural mechanisms dimensional label learning as a predictor of dimensional attention performance. From this, the quality and type of dimensional label learning can be better understood as an aid in explicit and implicit dimensional attention, allowing for a clearer picture of the attentional strategies used to successfully selectively attend, flexibly attend and stabilize attention to dimensions.

In this study, we administered the DLL tasks from Sandhofer and Smith (1999) along with the DCCS task, the DP task, and the TC task to a group of 3- to 4- year-olds while measuring fNIRS data from the left frontal, temporal, and parietal regions. These regions were chosen because the frontal and posterior regions have been previously implicated as important regions for high and low performance in the DCCS (Buss & Spencer, 2018). Further, the temporal and parietal regions have been implicated in object representation and the generation of color words implicated as important for visual representation (Martin, 2007; Martin et al., 1995).

The current study focuses on the neural dynamics of the word-word binding (Production task) and word-property binding (Comprehension task) DLL tasks as predictors for explicit (DCCS) and implicit (TC, DP, and Matching tasks) dimensional attention. Because the Matching task (property-property binding) uses selective attention

for successful performance, this task was grouped as an implicit dimensional attention task (Sandhofer & Smith, 1999).

This research aims to address two questions. First, does performance in the DLL task predict performance in the DCCS, DP, Matching, and TC tasks? Secondly, are there neural markers for DLL that predict performance on the DCCS, DP, Matching, and TC tasks? We predict that performance on the dimensional attention tasks will be related to one another. Specifically, that children who successfully switch in the DCCS will perform better in the TC, DP, and Matching tasks. Further, that the dimensional attention tasks will be positively correlated with one another. Lastly, we predict that neural activation during the DLL tasks will be associated with performance across the dimensional attention tasks. Specifically, that higher performers in the dimensional attention task will exhibit activation in the parietal/posterior regions in the dimensional label learning tasks, reflecting the findings of Buss and Spencer (2018).

CHAPTER 5: METHODS AND PROCEDURE

Participants

A total of 40 children were recruited into the study. Of those children, five children were dropped due to inability to complete the tasks, two children were dropped due to poor quality fNIRS collection, one child was dropped because fNIRS was not collected, and one child was dropped because they had autism spectrum disorder. The final dataset included a total of 31 children (mean age= 3.90 months; 13 females). Every parent signed an informed consent form before their child participated. All procedures were approved by the University of Tennessee, Knoxville IRB.

Task Procedure

In total, there were seven tasks performed: color priming, shape priming, DCCS, triad classification (TC), and three dimensional label learning (DLL) tasks (color comprehension, color production, and color matching). Tasks were administered in a fixed order, such that a priming task was first, followed by either the DCCS or TC, the DLL tasks, then DCCS or TC, and the remaining priming task. This order was chosen to counterbalance similar tasks and space out task demands throughout the study. Tasks were completed in one session with breaks in between each task. Each task was administered in E-Prime 2.0. Children sat in a chair in a dimly lit room 30-36 centimeters in front of a touch-screen monitor while completing each task.

Priming Tasks Procedure

Two versions of the DP task were administered: color priming and shape priming. In the color priming task, children were primed to sort by color whereas in the shape

priming task, children were primed to sort by shape. Both of the tasks started with a demo trial with physical cards. The experimenter showed the child a reference card (e.g., a blue heart) and two test objects (e.g., a blue circle and a yellow triangle). The experimenter then asked the child, “Which of these two [points to the test objects] goes with this one [points to reference card]?”. Once the child answered correctly, the experimenter asked, “Why do these two go together” to make sure the child understood the task before moving onto the computer version. Color and shape priming both started with two priming trials. The priming trial began with presentation of a reference object for 2500ms followed by two choice objects: one choice object would be the same across one dimension of the reference object, and the other choice object would be different along both dimensions from the reference object. The experimenter asked the child, “Which of these two [points to the test objects] goes with this one [points to reference object]?”. After this, 10 test trials were performed. The test trials differed from the priming trials in that one choice object shared a dimension with the reference object along the primed dimension (color or shape) and the other choice object shared the opposite dimension with the reference object (See Figure 2). The stimuli consisted of 9 colors (brown, red, green, black, pink, purple, orange, blue, and yellow) and 8 shapes (star, triangle, square, heart, diamond, cross, circle, and a 12-pointed-star). If the participant did not correctly answer both of the priming trials, they were dropped from data analysis. Based on this criteria, three participants were dropped from the DP color priming task, and no participants were dropped from the DP shape priming task.

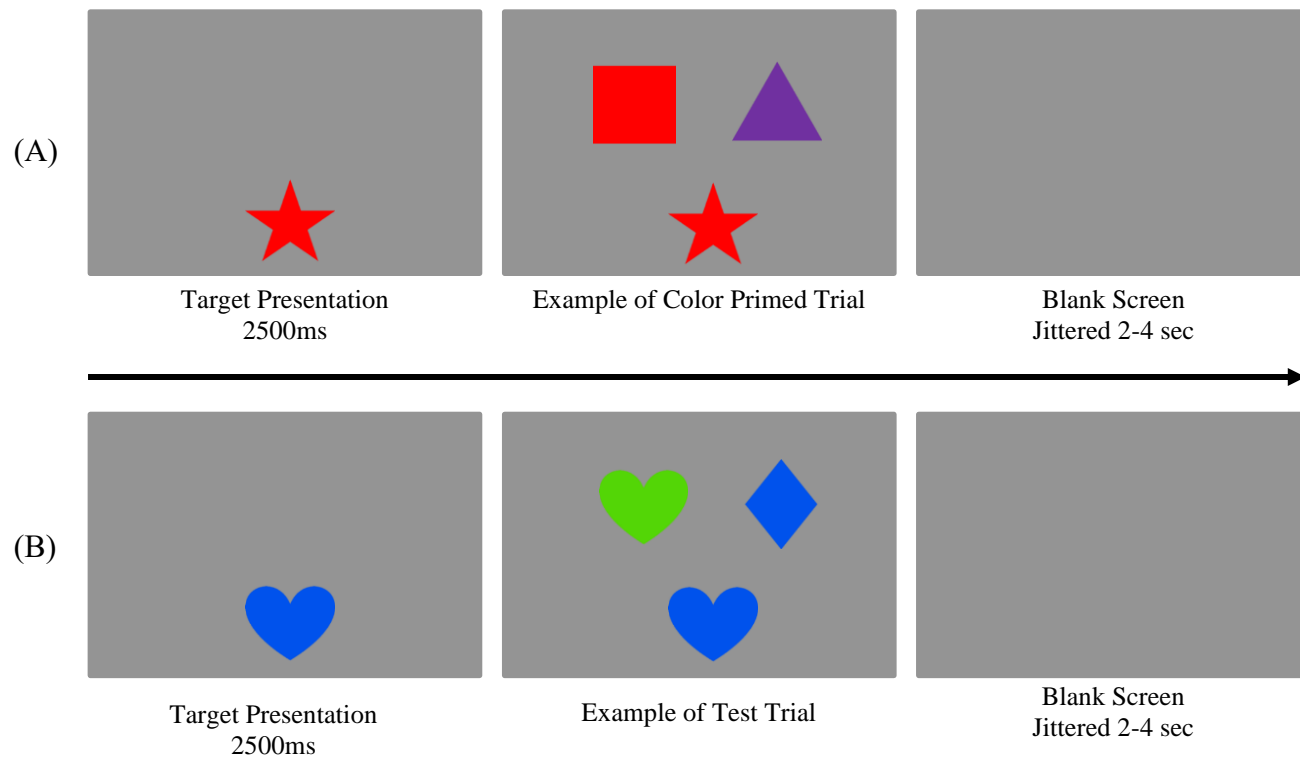


Figure 2. Dimensional Priming Task. (A) Example of a trial of the color priming task. (B) Example of a test trial.

DCCS Procedure

All procedures in the DCCS task followed a direct replication of the procedures in Buss and Kerr-German (2019). Children were first instructed for the DCCS with a set of trials using physical cards. Two cards were sorted by the experimenter to demonstrate the game, and then children were given 5 trials to perform on their own. Children were asked to sort by the dimension relevant to the pre-switch trials. Practice trials were not included in the analysis. Test cards were composed of a blue circle and red star. Target cards composed of red circles and blue stars. During the instructions, the experimenter introduced the game by saying, “This is a sorting game. It is called the (color/shape) game. In this game, we are going to sort by (color/shape). That means all of the (red ones/circles) go here and (blue ones/stars) go there.”

After the instructions and practice trials, children were given 5 pre-switch trials, and 5 post switch trials. During the pre- and post-switch phases, test card images were composed of a purple house and a yellow fish. After the pre- and post-switch phase, children completed 30 trials of mixed pre- and post- switch dimensions. During the mixed-block trials, the test card images consisted of a red bunny and a green chair. The mixed block included 10 trials of the pre-switch dimension and 20 trials of the post-switch dimension for a total of 30 trials.

Figure 3 depicts the sequence of trials for the DCCS. The task starts with a display of images showing sorting trails and target cards. During this screen, experimenters explained the rules of the game. Once the child was ready, the

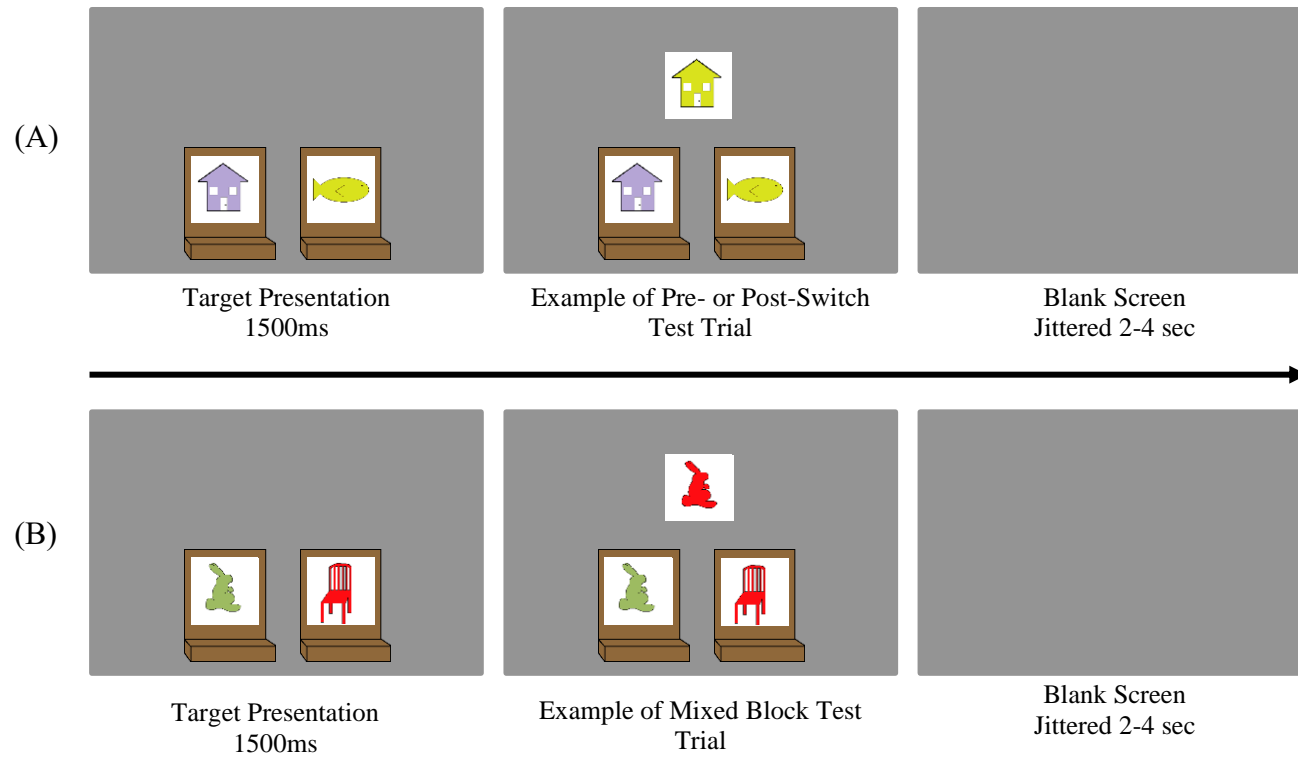


Figure 3. Dimensional Change Card Sorting Task. (A) Example of a pre- or post- switch trials of standard DCCS. (B) Example of a trial from the mixed block.

experimenter pressed the space bar to trigger the test card. After this, the experimenter said to the child, “Let’s play the (color/shape) game!” The child responded by pointing to one of the sorting trays. The child’s response was entered with a keyboard by the experimenter. When the pre-switch trials ended, the experimenter instructed the child to sort by the other dimension by saying, “We are all done with that game. Now we are going to play a new game. This new game is called the (shape/color) game. In this game we are going to sort by (shape/color). That means all of the (fish/yellow ones) go here and the (houses/purple ones) go there.” After this, post-switch trials proceeded similarly to the pre-switch trials. Once the pre- and post- switch trials were completed, the children were instructed that they were sometimes going to play the shape game, and sometimes going to play the color game. The experimenter then said, “If we are playing the color game, then you should sort by color. That means that all the red ones go here, and the green ones go there. If we are playing the shape game, then you should sort by shape. That means all the bunnies go here, and all the chairs go there.” After this, mixed-block trials proceeded similarly to the pre- and post-switch trials.

TC Procedure

All procedures in the TC task followed a direct replication of the procedures in Buss and Kerr-German (2019) based off of the original study by Smith and Kelmer (1977). In the TC task, children were asked to determine which objects “go together” and are the “most similar” to each other. First, children were shown the reference object on the screen and directed to its location by the experimenter. After 2.5 seconds, the ID and H choice objects popped up on the screen to the left and the right, the locations (left or

right) of the ID and H choice were randomized (Figure 4). Children were then instructed to pick the object that is most similar to the reference object. Children responded by pressing one of the choice objects on the computer touch screen. Out of the 40 total trials, 20 trials had a shape identity match, and 20 trials had a color identity match. Shape and color identity trials were randomized.

Stimuli in the TC task were constructed with metrically controlled shapes and colors. Shapes were constructed using Fourier components used in Drucker and Aguirre (2009), and colors were sampled from CIE L*a*b* (1976). Shapes and colors were taken from a list of 60 total items that were distinguished by 6 degrees in color space or shape space, see Figure 5 for examples of the stimuli used in the TC task. The current study based the holistic choice object values from the pilot data conducted in Buss and Kerr-German (2019), such that the holistic choice object could vary between 90 and 114 degrees in the color and shape space.

Dimensional Label Learning Tasks Procedure

DLL procedure followed the procedures in Lowery et al. (2018) based off of the original study by Sandhofer and Smith (1999). In this task, there were 3 different DLL tasks: production, comprehension, and matching. Each task was repeated 3 times for 6 trials each, a total of 54 trials (18 trials per task). The stimuli consisted of six shapes (flower, star, shoes, key, chair, and heart) and six colors (red, blue, yellow, green, purple, orange). Shape and color were randomized throughout the task. In the production task, children were shown a single object and asked, “What color is this?”. The experimenter entered the child’s response as either correct, incorrect or no response/ “I don’t know”. In

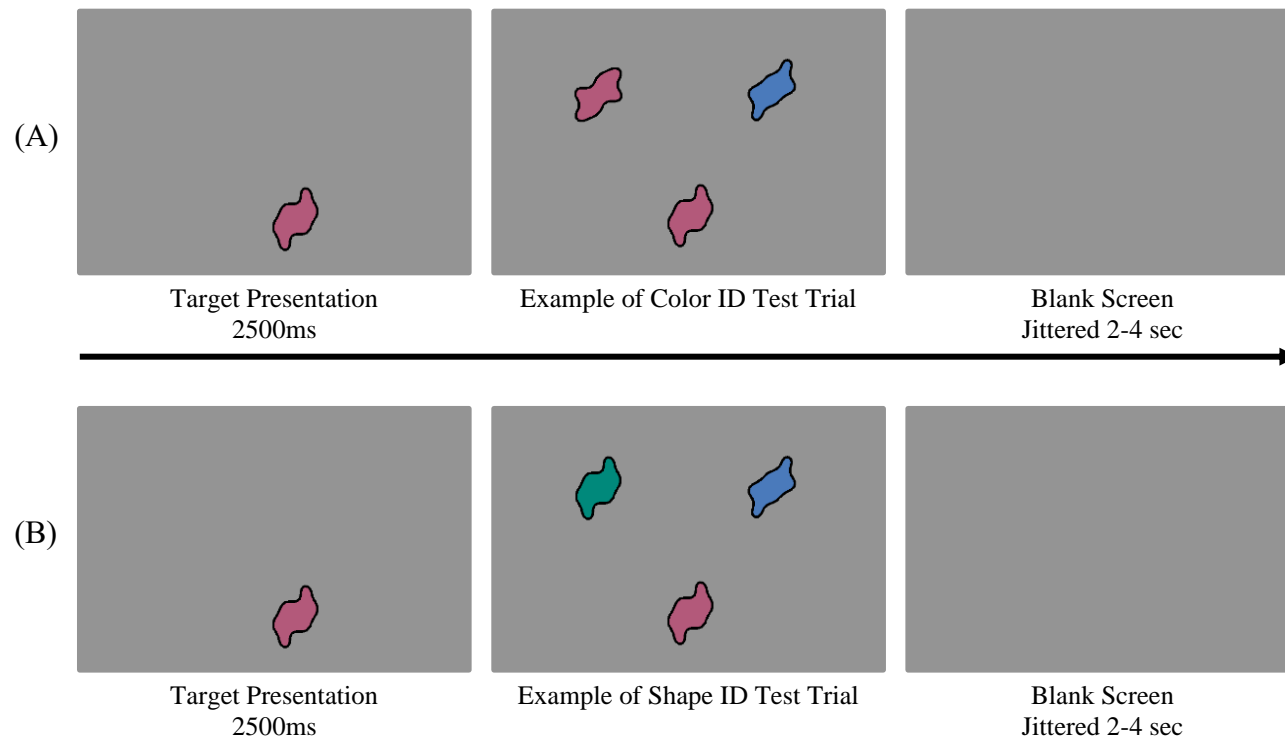


Figure 4. Triad Classification. (A) Example of a color identity trial. (B) Example of a shape identity trial.

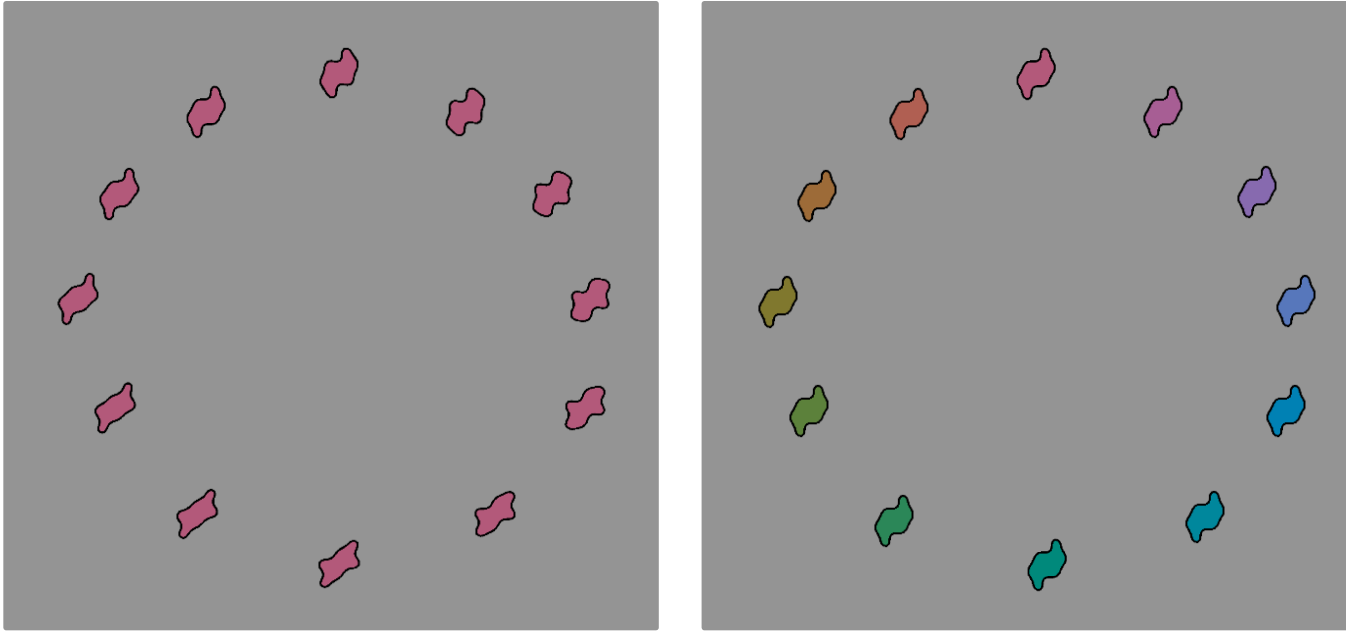


Figure 5. Triad Classification stimuli. Depiction of shape-space and color-space used in the triad classification task

the comprehension task, children were shown a circular array of six different objects and asked, “Which one is red?”, for example. Children responded by pressing an object on a computer touch screen. In the comparison task, children were shown two reference objects of the same color followed by an array of 6 different objects in a semicircle above the two reference objects. Experimenters asked the child, “Do you see how these two are the same? [pointing at the two reference objects] Which one of these [pointing to the other six objects] is the same like these two [pointing at the two reference objects?” Children responded by pressing one of the six objects (see Figure 6).

fNIRS Data Collection

The child’s head was measured, and the vertex was marked. The fNIRS cap was placed on their head and digitization of the fNIRS probe was made using a Polhemus motion tracking system marking the probe’s location relative to landmarks (nasion, inion, left tragus, right tragus, and vertex). fNIRS data were collected at 25Hz using a Techon CW7 system with wavelengths of 830nm and 690nm. Light was delivered through fiber optic cables that terminated in a probe compiled of 4 sources and 8 detectors placed 3cm apart for a total of 12 channels. Sources were arranged in the 10-20 system over the left frontal cortex, left temporal cortex, and left parietal cortex (Figure 7). The left cortex was measured because the left hemisphere includes the language center of the brain (Martin et al., 1995).

fNIRS Data Analysis

For this experiment, we were interested in how the neural data related to the DLL tasks predicted the dimensional attention tasks. Therefore, we only analyzed the DLL

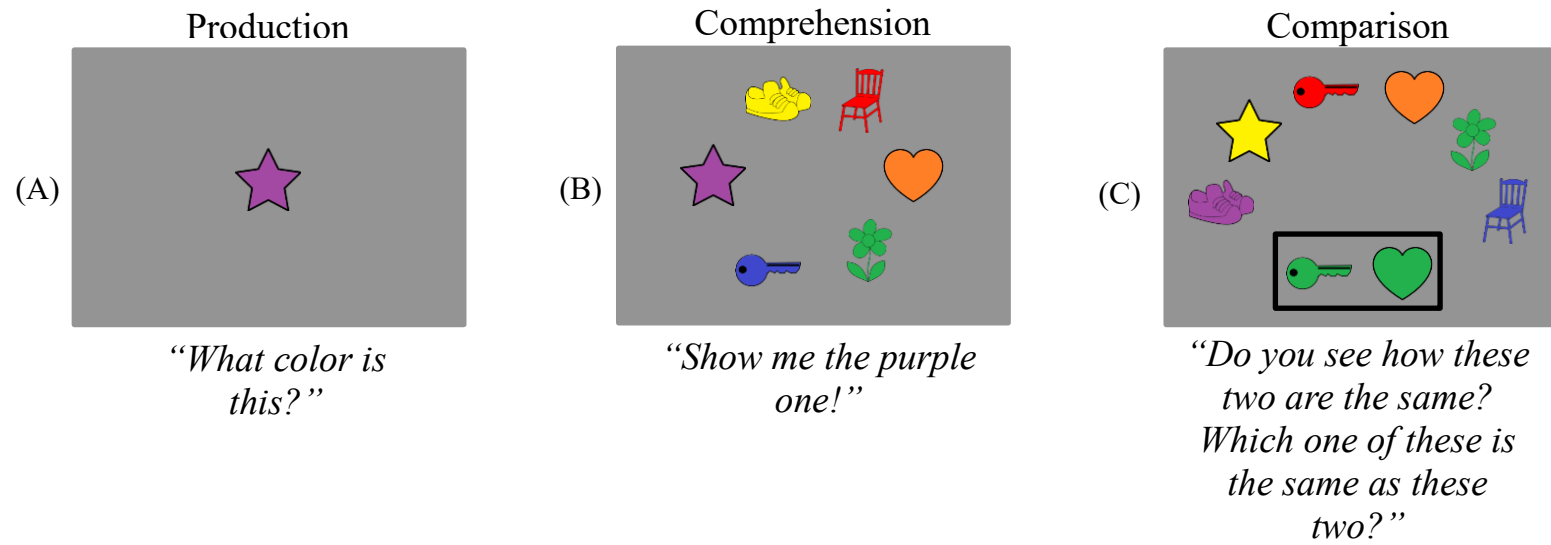


Figure 6. Dimensional Label Learning Tasks. (A) Example of a Production task trial. (B) Example of a Comprehension task trial. (C) Example of a Comparison task trial.

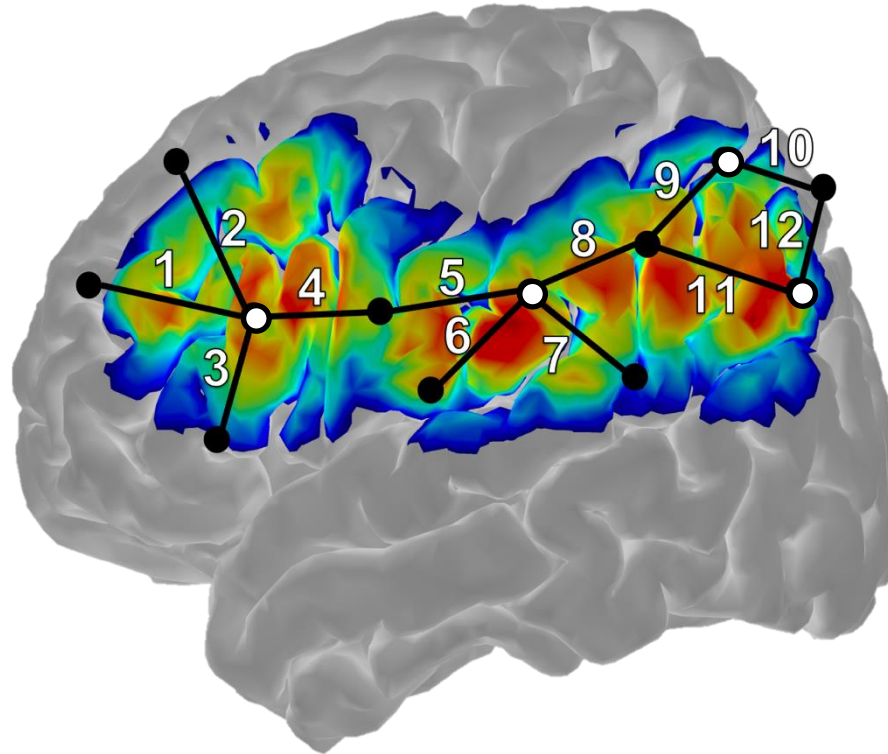


Figure 7. This figure depicts the sensitivity profile for the fNIRS probe used the current study. White circles indicate light placement whereas black circles indicate detector placement.

neural data. Trials with slow reaction time (2.5 SDs above the mean reaction time) in the Production ($M=4400\text{ms}$, cutoff= 14200), Comprehension ($M=3800\text{ms}$, cutoff= 12200), and Matching ($M=4830\text{ms}$, cutoff= 15400) tasks or fast reaction time (less than 500ms) were eliminated. As a results, a total of 3.63% of trials were eliminated from analysis due to bad reaction time. The average amplitude of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) were calculated for each trial type of each channel within the time range of 2 seconds before stimulus onset and 12 seconds after the stimulus.

In the fNIRS data analysis, activation is defined as an increase in HbO and a decrease in HbR (Tachtsidis & Scholkmann, 2016). For each task, children were grouped based on a median split of their behavioral performance in each of the dimensional attention tasks as a between-subject factor. EasyNIRS HomER2 software (Huppert et al., 2009) was used to calculate the mean baseline and transform the data into an optical density measure. An interquartile range of 1.5 with a wavelet-based motion artifact removal tool within EasyNIRS was used to correct motion artifacts. The data were then band-pass filtered (high-pass filter= 0.01 , low-pass filter= 0.50 ; partial pathlength factor values of 6.0 and 6.0). Then, the data were converted to absolute 3 concentration values using the modified Beer-Lambert Law (Boas et al., 2001). Mixed-factor ANOVAs were used to analyze the changes in HbO and HbR based on performance in the dimensional attention tasks.

CHAPTER 6: RESULTS

Statistical Analysis for Accuracy in Tasks

All accuracy data for each task performed are reported in Figure 8. Three paired-samples t-test were performed to test if accuracy differed significantly between the DLL tasks. It was found that in the Production task ($M=0.95$, $SD=0.09$) did not differ from accuracy in the Comprehension task ($M=0.94$, $SD=0.11$), $t(30)=1.36$, $p=.184$, or from accuracy in the Matching task ($M=0.86$, $SD=0.26$), $t(30)=1.66$, $p=.108$. Further, accuracy in the Comprehension task ($M=0.94$, $SD=0.11$) did not differ from accuracy in the Matching task ($M=0.86$, $SD=0.26$), $t(30)=1.29$ $p=.205$.

Additionally, a paired-samples t-test was performed to test if accuracy differed between similar dimensional attention tasks, specifically Color and Shape DP tasks and Color and Shape TC trials. It was found that accuracy for the DP Shape Task ($M=0.79$, $SD=0.29$) did not differ from accuracy in the DP Color Task ($M=0.65$, $SD=0.31$), $t(27)=1.58$, $p=.125$. Performance in the DP Shape Task ($M=0.79$, $SD=0.29$; $t(30)=3.07$, $p=.005$) and the DP Color Task ($M=0.65$, $SD=0.31$; $t(27)=5.28$, $p<.001$) were significantly higher than chance performance ($M=0.50$). In the TC tasks, accuracy for color trials ($M=0.66$, $SD=0.24$) did not differ from accuracy for shape trials ($M=0.62$, $SD=0.18$), $t(30)=0.65$, $p=.523$. Performance in the TC color trials ($M=0.66$, $SD=0.24$; $t(30)=3.65$, $p=.001$) and the TC shape trials ($M=0.62$, $SD=0.18$; $t(30)=3.85$, $p=.001$) were significantly higher than chance performance ($M=0.50$).

Correlations were performed for accuracy in all tasks (DP Color, DP Shape, TC Color Trials, TC Shape Trials, DCCS Mixed Block Accuracy, Production,

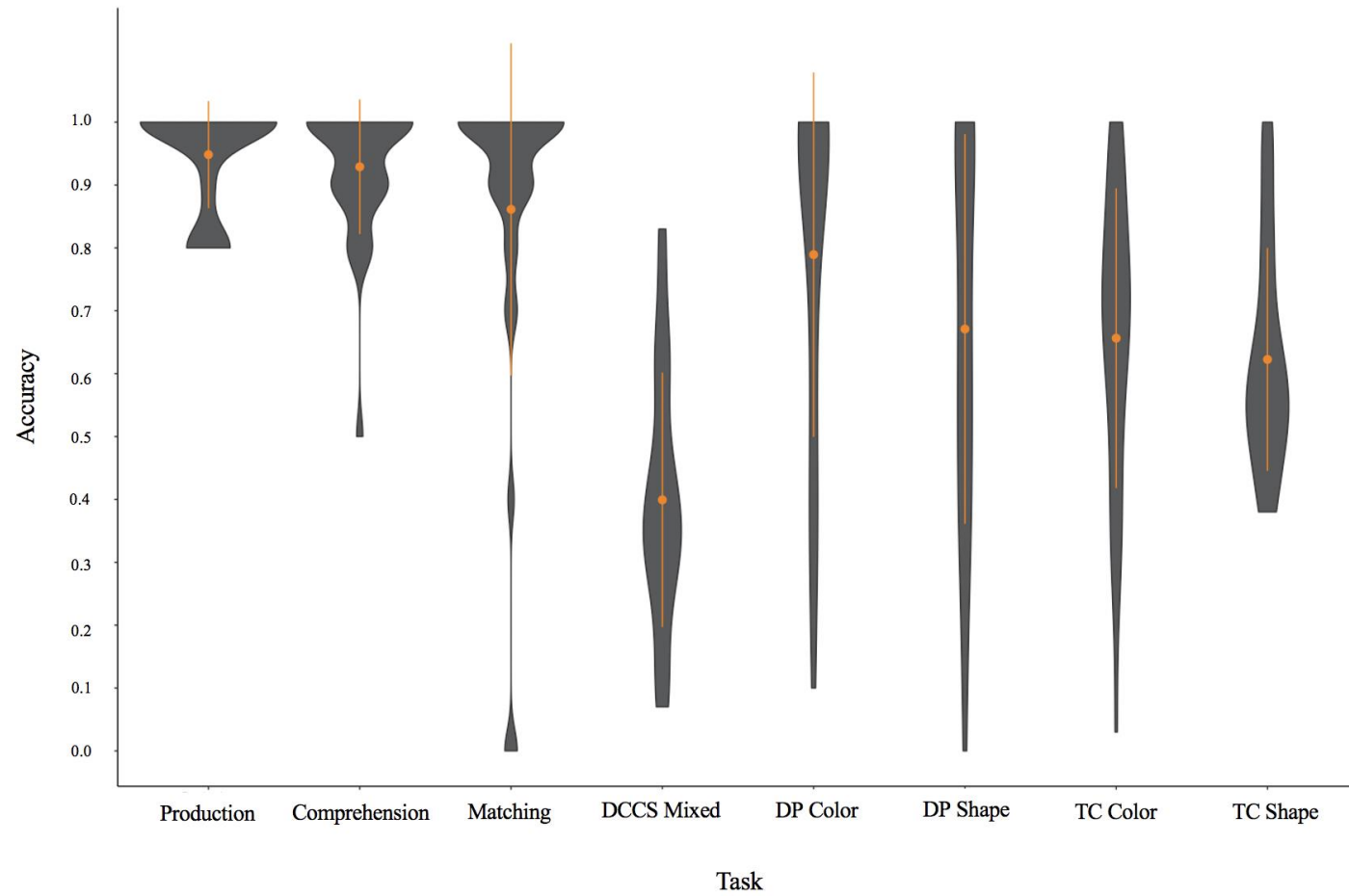


Figure 8. This figure depicts violin plots of accuracy across tasks. Dots and lines depicts means and standard deviations of each task performance.

Comprehension, and Matching) to better understand the relationship between the dimensional attention tasks and the DLL tasks. See Table 1 for a complete correlation table. DP Color accuracy was negatively correlated with accuracy in the DCCS mixed block, $r(25) = -.568, p = .004$. Further, DP Color accuracy was positively correlated with accuracy in the Matching task, $r(28) = .434, p = .021$. Matching accuracy was also positively correlated with accuracy in the color trials of the TC task, $r(31) = .405, p = .024$. Lastly, Comprehension accuracy was strongly positively correlated with Production accuracy, $r(28) = .682, p < .001$.

DCCS post switch performance as a Predictor for Performance

To understand if DCCS post-switch performance predicted their performance in the DCCS mixed block, an independent samples t-test was performed and showed that children who perseverated in the DCCS ($M = 0.38, SD = 0.26$) did not differ from children who successfully switched in the DCCS ($M = 0.40, SD = 0.09$), $t(18.0) = -0.209, p = .837$ (adjusted for unequal variances) in DCCS mixed block accuracy. To test if task order in the DCCS had an effect on whether or not children passed the post switch phase, a Chi-Square test was performed and found that there was no association between task order in the DCCS (color-shape, shape-color) and DCCS post switch performance (switched, perseverated), $\chi^2(1) = 2.77, p = .096$.

Next, children were grouped based on whether they passed the post-switch phase of the DCCS to examine associations with performance on the other tasks. Accuracy in the Production Task ($t(25) < 1, p = .922$), Comprehension Task ($t(25) = -1.05, p = .304$), Matching Task ($t(25) = -.51, p = .612$), TC task ($t(25) = 0.49, p = .625$), and DP Color Task

Table 1. Correlations for Task Accuracy

	DP Color Accuracy	DP Shape Accuracy	TC Color Accuracy	TC Shape Accuracy	DCCS Mixed Block Accuracy	Production Accuracy	Comprehension Accuracy	Matching Accuracy
DP Color Accuracy	1							
DP Shape Accuracy	-0.190	1						
TC Color Accuracy	0.269	-0.222	1					
TC Shape Accuracy	-0.003	0.098	0.036	1				
DCCS Mixed Block Accuracy	-0.568**	-0.180	-0.234	-0.167	1			
Production Accuracy	0.062	-0.122	-0.146	0.047	0.114	1		
Comprehension Accuracy	0.147	-0.134	-0.082	0.080	0.065	0.682**	1	
Matching Accuracy	0.434*	-0.348	0.405*	-0.115	-0.289	-0.196	-0.065	1

** . Correlation is significant at the 0.01 level (2-tailed)

* . Correlation is significant at the 0.05 level (2-tailed)

($t(20.3) = -0.563$, $p = .580$; adjusted for unequal variances) did not differ between groups.

However, we found that children who switched in the DCCS ($M = 0.81$ $SD = 0.24$) performed better in the DP Shape task than children who perseverated ($M = 0.59$ $SD = .28$), $t(25) = 2.14$, $p = .042$.

To examine whether performance on the DCCS task is related to task dimension in the DP and TC tasks, a 2 (task: TC and DP) x 2 (dimension: color, shape) x 2 (DCCS: switch, perseverated) mixed ANOVA was performed. This analysis revealed no significant main effect of dimension ($F(1,22) = 1.67$, $p = .210$, $\eta_p^2 = .070$), but did find a marginally significant main effect of task such that the DP task accuracy ($M = 0.73$, $SD = 0.04$) was marginally higher than the TC accuracy ($M = 0.65$, $SD = 0.03$; $F(1,22) = 3.97$, $p = .059$, $\eta_p^2 = .153$) and a significant interaction between dimension and DCCS post switch performance, $F(1,22) = 4.43$, $p = .047$, $\eta_p^2 = .168$. Pairwise comparisons using the Bonferroni adjustment found that children who successfully switched in the DCCS ($M = 0.74$, $SD = 0.04$) performed better on the shape dimensions in the DP and TC tasks than children who perseverated ($M = 0.58$, $SD = 0.05$), $p = .025$. Further, children who perseverated in the DCCS did better on the color dimension in the DP and TC tasks ($M = 0.77$, $SD = 0.06$) than on the shape dimension in the DP and TC tasks ($M = 0.58$, $SD = 0.05$), $p = .031$ (Figure 9)

Hemodynamics during the Production and Comprehension Task

To examine neural activation during the DLL tasks, a 2 x 2 ANOVA was performed with chromophore (HbO, HbR) and task type (Production, Comprehension) for each channel. A main effect of chromophore showed deactivation over the frontal

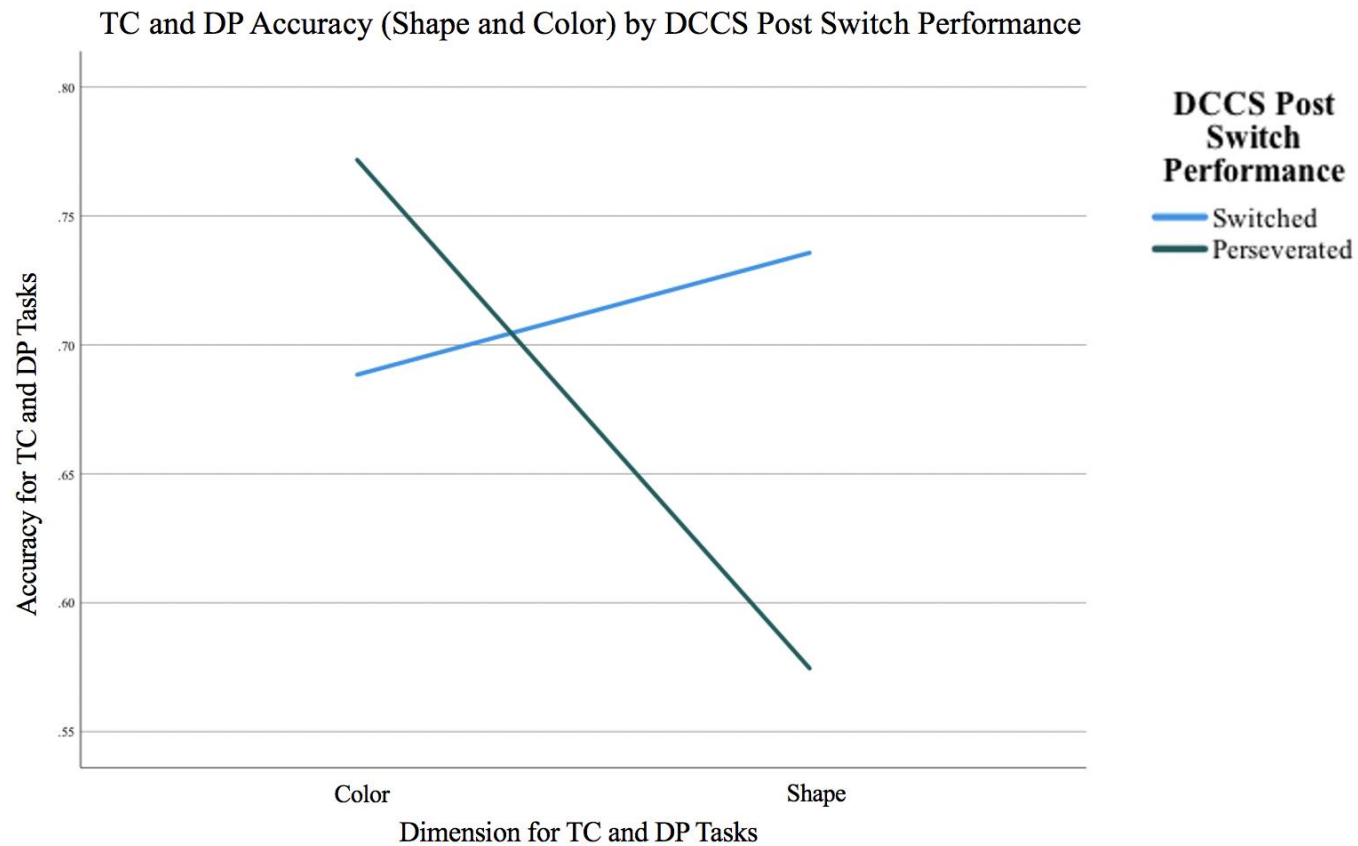


Figure 9. This figure depicts the interaction for TC and DP Accuracy between TC and DP trials by dimension (shape and color) and performance on the DCCS Post Switch phase. For the shape trials, children who successfully switched in the DCCS performed better than children who perseverated in the DCCS. Children who perseverated on the DCCS did better on color trials when compared to shape trials.

cortex (channel 1: $F(1,30)=5.95, p=.021, \eta_p^2=.166$; channel 2, marginal: $F(1,30)=3.78, p=.061, \eta_p^2=.112$) such that HbR ($M=0.08, SD=0.05$ for channel 1; $M=0.06, SD=0.06$ for channel 2) was significantly higher than HbO ($M=-0.05, SD=0.06$ for channel 1; $M=-0.03, SD=0.05$ for channel 2). Additionally, a main effect of Chromophore showed activation over the temporal cortex (channel 7: $F(1,30)=10.42, p=.003, \eta_p^2=.258$; channel 8: $F(1,30)=6.39, p=.017, \eta_p^2=.175$) such that HbO ($M=0.12, SD=0.07$; $M=0.16, SD=0.05$) was significantly higher than HbR ($M=0.05, SD=0.06$; $M=0.03, SD=0.03$; See Figure 10) No other effects reached significance.

Hemodynamics of the Production Task Predicting Dimensional Attention Performance

Next, we examined whether neural activation from the Production task was associated with performance on the dimensional attention tasks. Each dimensional attention task was classified as high performers or low performers based off of a median split. A 2 x 2 ANOVA was performed with chromophore (HbO, HbR) during the Production task and performance (high, low) of each dimensional attention task for every channel. An interaction between Chromophore and TC task performance was found over the left temporal cortex (channel 6), $F(1,29)=5.92, p=.021, \eta_p^2=.170$. Pairwise comparisons using the Bonferroni adjustment found significant deactivation in the left temporal cortex for high TC task performers such that HbR ($M=0.13, SD=0.06$) was significantly larger than HbO ($M=-0.10, SD=0.08$), $p=.031$. An interaction between Chromophore and Matching task Performance was found over the left temporal cortex (channel 6), $F(1,29)=4.49, p=.043, \eta_p^2=.134$. Pairwise comparisons using the Bonferroni adjustment found marginally significant deactivation in the left temporal cortex for high Matching

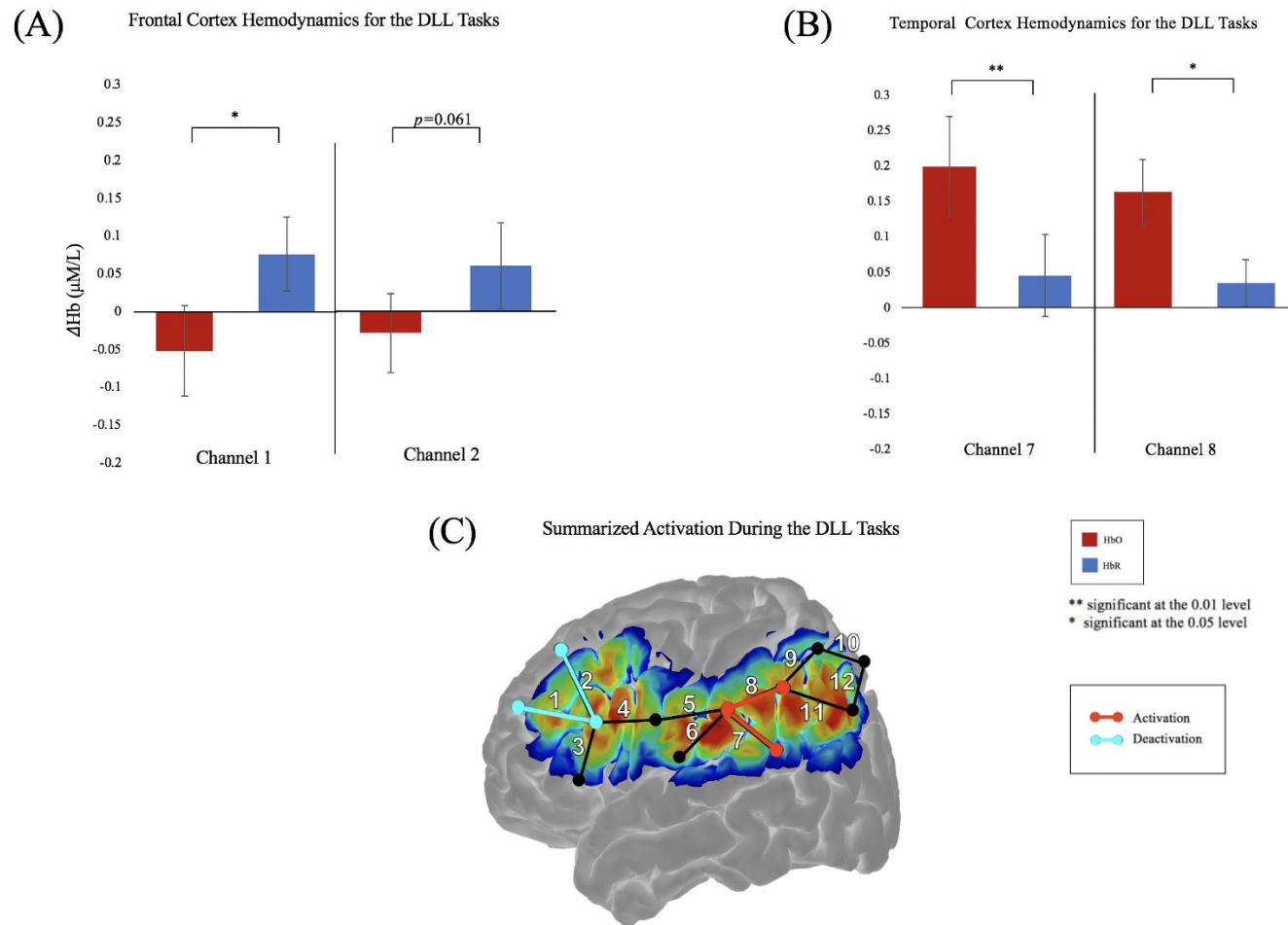


Figure 10. Neural activation during the Production and Comprehension tasks. (A) Changes in hemoglobin in the frontal cortex during the DLL tasks. (B) Changes in hemoglobin in the temporal cortex during the DLL Tasks. (C) Summary of activation and deactivation during the DLL Tasks.

task performers such that HbR ($M=0.13$, $SD=0.06$) was marginally larger than HbO ($M=-0.05$, $SD=0.07$), $p=.064$ (see Figure 11).

An interaction between Chromophore and Matching Performance was found over left parietal cortex (channel 8), $F(1,29)=5.63$, $p=.024$, $\eta_p^2=.163$. Pairwise comparisons using the Bonferroni adjustment found significant activation for low performers in the Matching Task such that HbO ($M=0.28$, $SD=0.06$) was significantly higher than HbR ($M=0.04$, $SD=0.09$), $p=.048$. A main effect of Chromophore showed activation over the left parietal cortex (channel 10) for both high and low performers of the DCCS post switch phase (marginal; $F(1,25)=3.18$, $p=.087$, $\eta_p^2=.113$), TC task ($F(1,29)=5.05$, $p=.033$, $\eta_p^2=.148$), DP shape task ($F(1,29)=4.65$, $p=.040$, $\eta_p^2=.138$), and Matching Task (marginal; $F(1,29)=4.01$, $p=.055$, $\eta_p^2=.121$) such that HbO was larger than HbR (see Figure 11). An interaction between Chromophore and TC Task Performance was found over the left parietal cortex (channel 10), $F(1,29)=4.54$, $p=.042$, $\eta_p^2=.135$. Pairwise comparisons using the Bonferroni adjustment found significant activation in the left parietal cortex for high TC task performers such that HbO ($M=0.23$, $SD=0.17$) was significantly larger than HbR ($M=-0.25$, $SD=0.08$), $p=.006$ (see Figure 11). No other effects reached significance.

Hemodynamics of the Comprehension Task Predicting Dimensional Attention Performance

The analysis of the Comprehension Task hemodynamics was performed the same as the Production Task hemodynamics. A 2 x 2 ANOVA was performed with

(A)

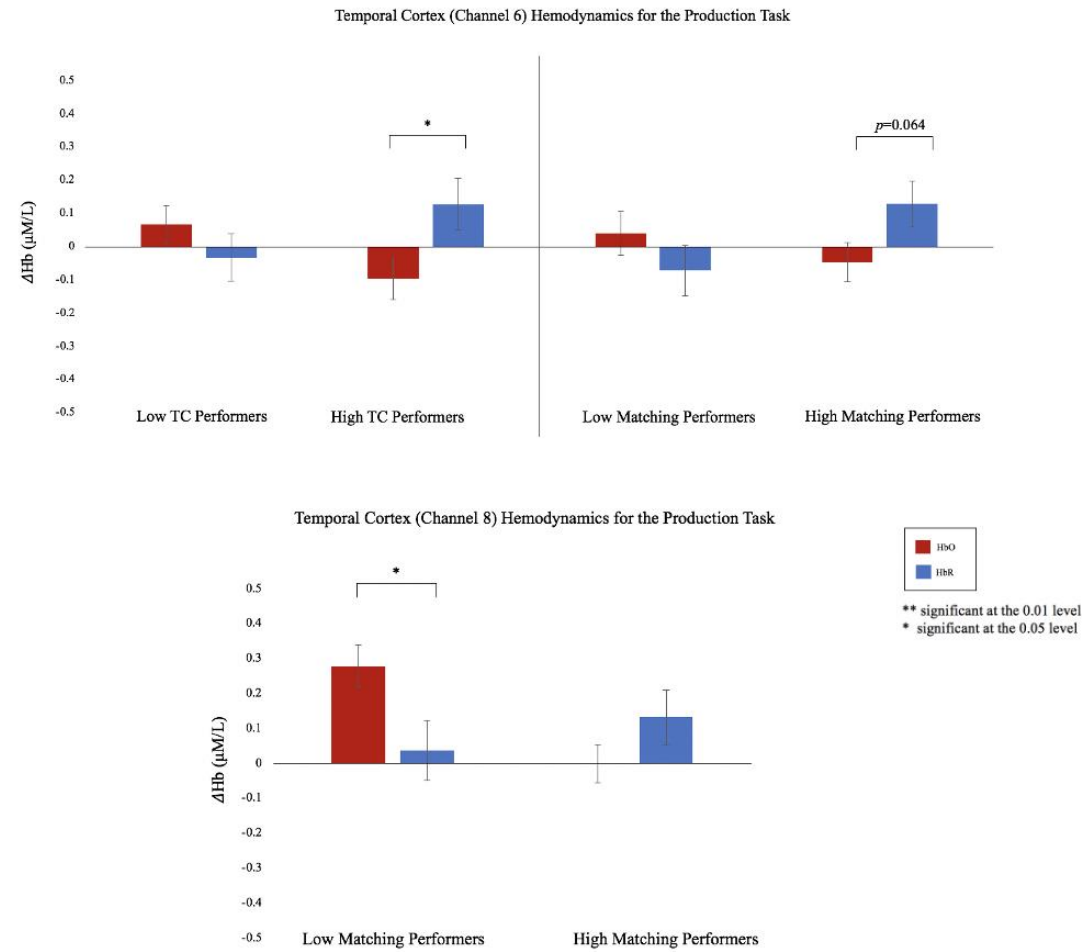


Figure 11. Neural activation during the Production task predicting high and low performance on the dimensional attention tasks. (A) Changes in hemoglobin in the temporal cortex during the Production task as a marker for high and low DA performance.

(B)

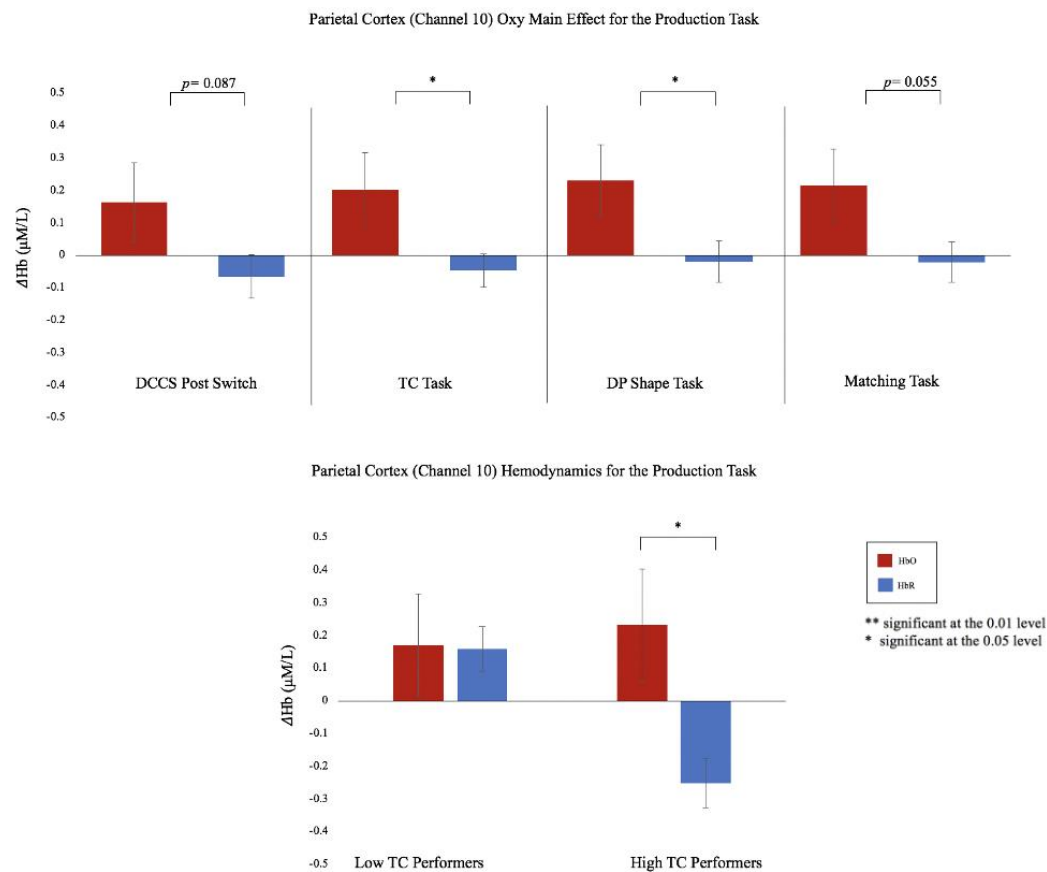


Figure 11 (continued). (B) Changes in hemoglobin in the parietal cortex during the Production task as a marker for high and low DA performance.

(C)

Summarized Activation During the Production Task for High and Low Dimensional Attention Performers

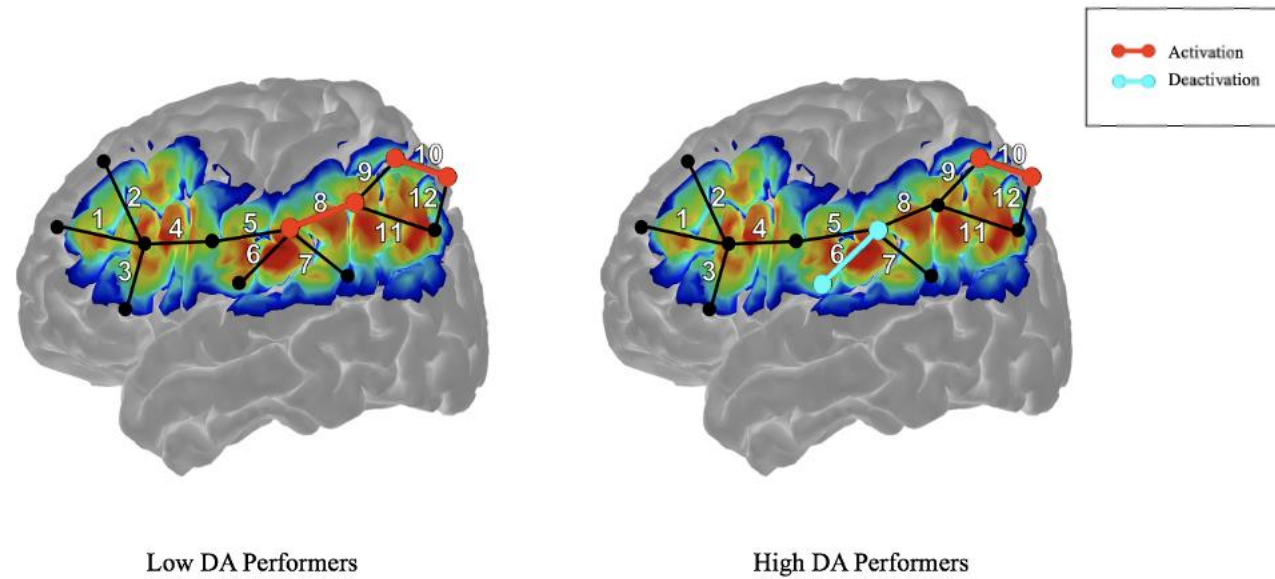


Figure 11 (continued). (C) Summary of activation and deactivation during the Production Task for high and low DA performance.

chromophore (HbO, HbR) during the Comprehension Task and performance (high, low) of each dimensional attention task for every channel.

A main effect of Chromophore showed deactivation over left frontal cortex (channel 1) for both high and low performers of the DCCS Mixed Block ($F(1,25)=4.82$, $p=.038$, $\eta_p^2=.162$), DCCS post switch phase ($F(1,25)=5.27$, $p=.030$, $\eta_p^2=.174$), TC task ($F(1,29)=7.43$, $p=.011$, $\eta_p^2=.204$), DP Color task ($F(1,26)=4.38$, $p=.046$, $\eta_p^2=.144$), DP Shape task ($F(1,29)=6.38$, $p=.004$, $\eta_p^2=.180$), and Matching task ($F(1,29)=5.98$, $p=.021$, $\eta_p^2=.171$). Further, a marginal interaction between Chromophore and DP Color Performance was found over the left frontal cortex (channel 1), $F(1,26)=3.32$, $p=.080$, $\eta_p^2=.113$. Pairwise comparisons using the Bonferroni adjustment found significant deactivation in high DP Color Task performers such that HbR ($M=0.13$, $SD=0.07$) was significantly higher than HbO ($M=-0.11$, $SD=0.09$), $p=.010$. A main effect of Chromophore showed deactivation over the left frontal cortex (channel 2) for both high and low performers of the TC task ($F(1,29)=5.22$, $p=.030$, $\eta_p^2=.152$), DP Shape task ($F(1,29)=5.36$, $p=.028$, $\eta_p^2=.156$), and Matching task ($F(1,29)=4.63$, $p=.040$, $\eta_p^2=.138$). An interaction between Chromophore and TC task Performance was found over the left frontal cortex (channel 3), $F(1,29)=4.94$, $p=.034$, $\eta_p^2=.146$. Pairwise comparisons using the Bonferroni adjustment found significant activation in low TC task performers such that HbO ($M=0.44$, $SD=.167$) was significantly higher than HbR ($M=-0.09$, $SD=0.13$), $p=.016$ (See Figure 12).

A main effect of Chromophore over the temporal cortex (channel 7) showed activation in both low and high performers of the DCCS Mixed Block ($F(1,25)=7.47$,

(A)

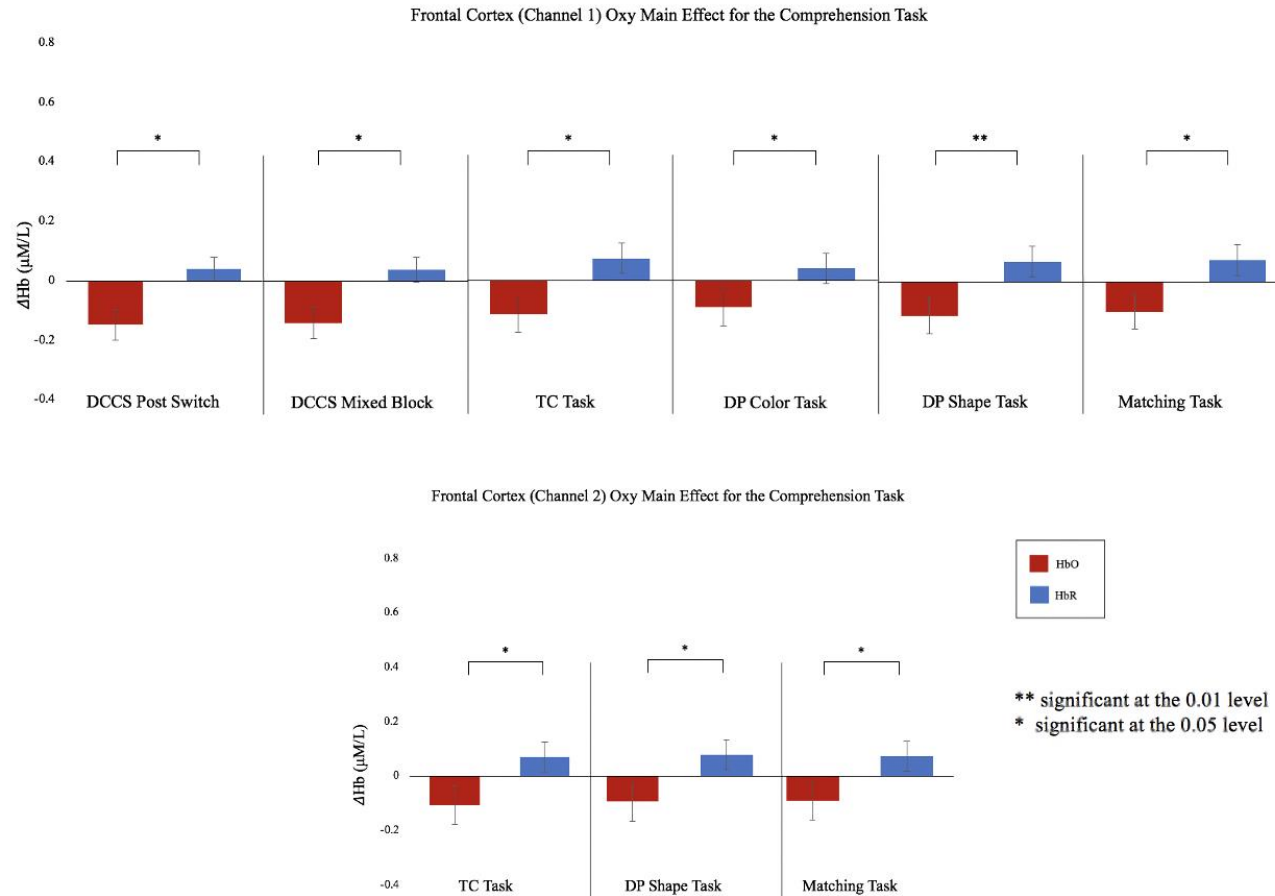


Figure 12. Neural activation during the Comprehension task predicting high and low performance on the dimensional attention tasks. (A) Changes in hemoglobin in the frontal cortex during the Comprehension task as a marker for high and low DA performance.

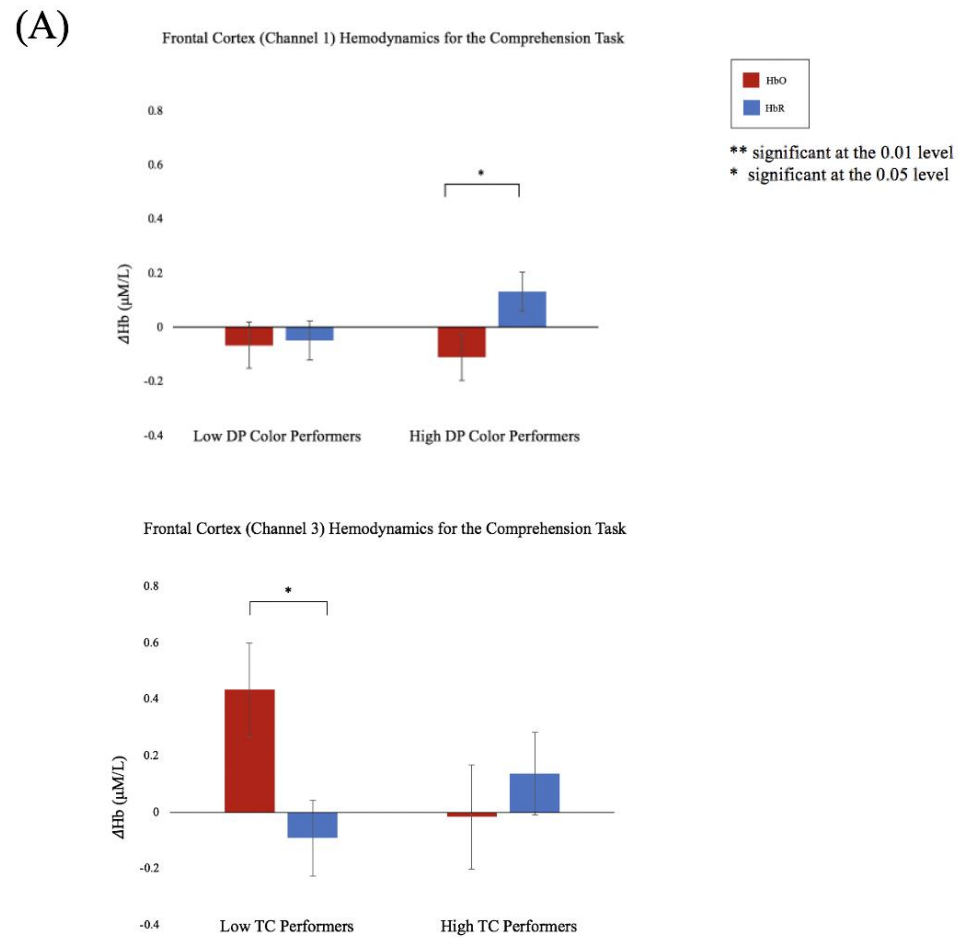


Figure 12 (continued). (A) Changes in hemoglobin in the frontal cortex during the Comprehension task as a marker for high and low DA performance.

(B)

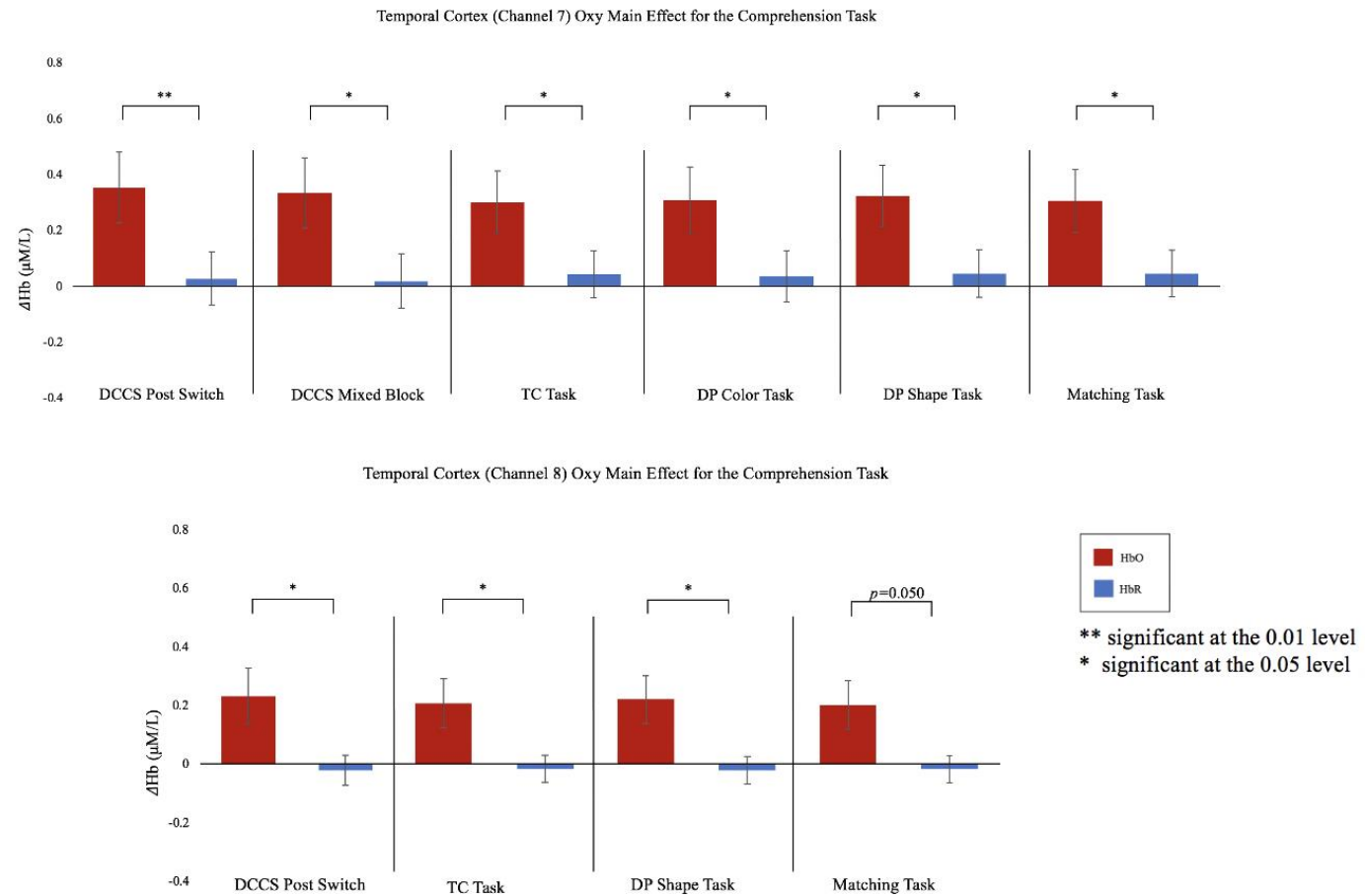


Figure 12 (continued). (B) Changes in hemoglobin in the temporal cortex during the Comprehension task as a marker for high and low DA performance.

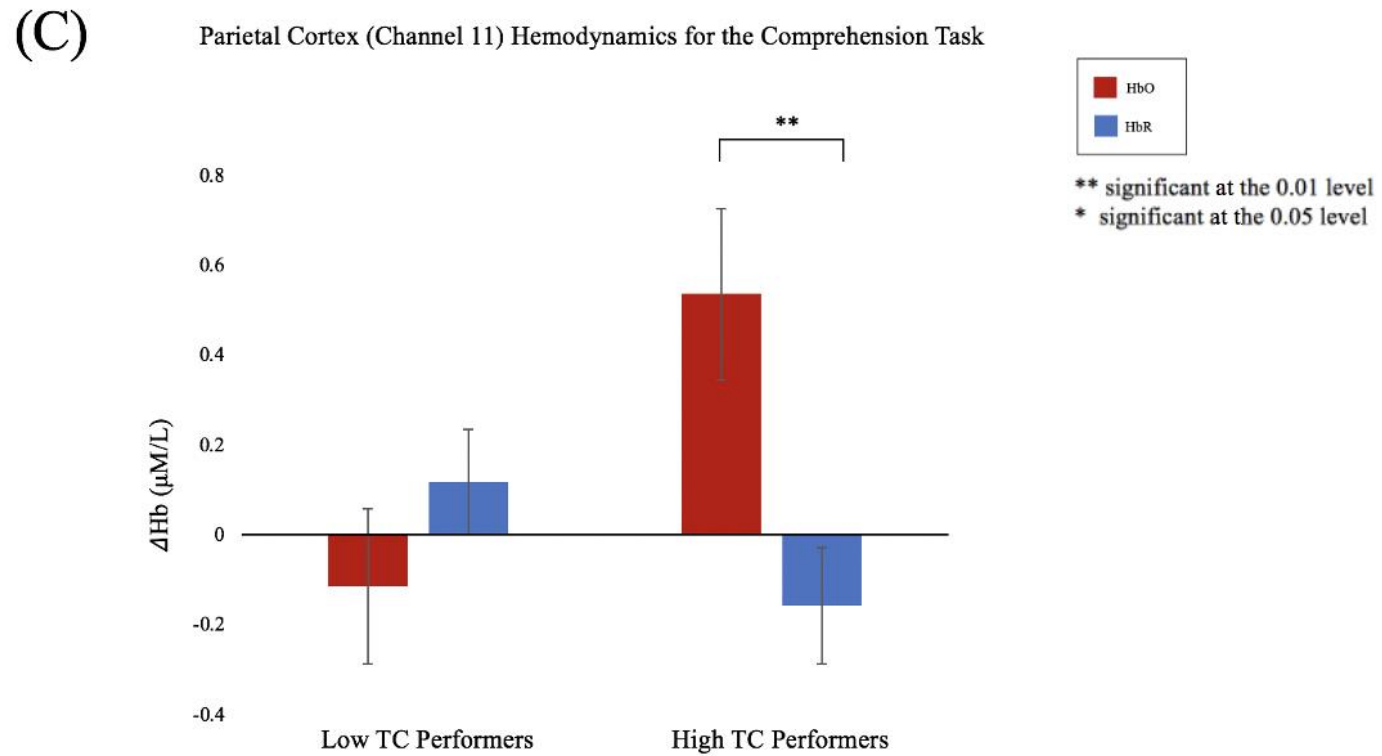


Figure 12 (continued). (C) Changes in hemoglobin in the parietal cortex during the Comprehension task as a marker for high and low TC task performance.

(D)

Summarized Activation During the Comprehension Task for High and Low Dimensional Attention Performers

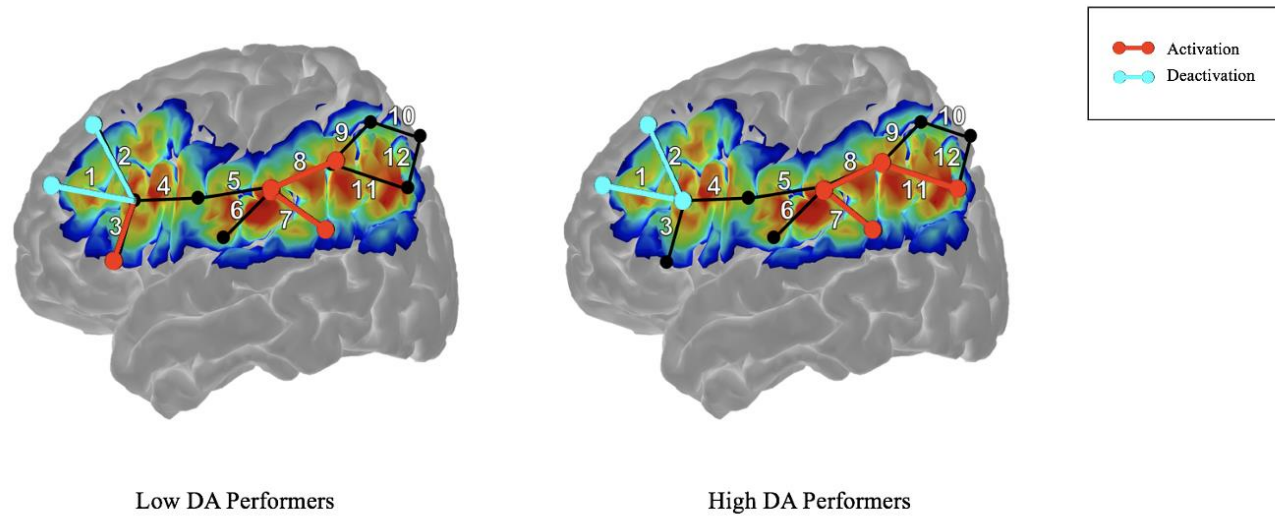


Figure 12 (continued). (D) Summary of activation and deactivation during the Comprehension Task for high and low DA performance.

$p=.011$, $\eta_p^2 = .230$), DCCS post switch phase ($F(1,25)=8.59$, $p=.007$, $\eta_p^2 = .256$), TC task ($F(1,29)=6.35$, $p=.017$, $\eta_p^2 = .180$), DP Color task ($F(1,26)=6.05$, $p=.021$, $\eta_p^2 = .189$), DP Shape task ($F(1,29)=7.30$, $p=.011$, $\eta_p^2 = .201$), and Matching task ($F(1,29)=6.49$, $p=.016$, $\eta_p^2 = .183$). Further, a main effect of Chromophore over the temporal cortex (channel 8) showed activation in both low and high performers of the DCCS post switch phase ($F(1,25)=4.42$, $p=.046$, $\eta_p^2 = .150$), TC Task ($F(1,29)=4.44$, $p=.044$, $\eta_p^2 = .133$), DP Shape Task ($F(1,29)=5.40$, $p=.027$, $\eta_p^2 = .157$), and Matching Task (marginal; $F(1,29)=4.18$, $p=.050$, $\eta_p^2 = .126$; see Figure 12).

Lastly, an interaction between Chromophore and TC task Performance was found over the left parietal cortex (channel 11), $F(1,29)=7.95$, $p=.009$, $\eta_p^2 = .215$. Pairwise comparisons using the Bonferroni adjustment found significant activation in high TC task performers such that HbO ($M=0.54$, $SD=0.19$) was significantly higher than HbR ($M=-0.16$, $SD=0.13$), $p=0.008$ (Figure 12). No other effects reached significance.

CHAPTER 7: DISCUSSION

The current study aimed to understand how the neural correlates of dimensional label learning relates to dimensional attention. First, the results indicate that high performers of flexible attention perform better on shape related dimensional attention tasks than children who perseverated in the DCCS. This could be due to a gap in understanding between high and low performers of shape labels compared to color labels. In Buss and Nikam (2019), it was found that children are exposed to color labels significantly more than shape labels. It was found that when switching to shape in the DCCS, children perseverated at a higher rate when only dimensional labels were provided (Buss & Nikam, 2019). The current study builds on these previous findings by showing that children who persevereate also have a more difficult time with shape in other dimensional attention tasks.

Second, it was found that across participants, the temporal cortex was activated during the Production and Comprehension tasks. It has been found in previous research that activation in temporal and parietal areas have been implicated in object representation and the generation of color words suggesting that children may be using object-label binding during the DLL tasks (Martin, 2007; Martin et al., 1995).

Third, successful performance on the dimensional attention tasks was associated with activation in the parietal cortex for both Comprehension and Production tasks. On the other hand, low performance on the dimensional attention task was marked with activation in the temporal cortex for the Production task, and activation of the ventrolateral prefrontal cortex for the Comprehension task. The frontal cortex has been

implicated in semantic memory suggesting that low dimensional attention performers are retrieving lexical and semantic information while completing the Comprehension task (Martin & Chao, 2001). Additionally, previous research has found that posterior cortical activation is seen in older children during the DCCS, reflecting refinement of brain networks in skilled children (Buss & Spencer, 2018). In the current study, high dimensional attention performers showed similar activation patterns during the DLL tasks, reflecting a similar neural pattern as skilled DCCS performers in Buss and Spencer (2018).

Surprisingly, DP Color task accuracy was negatively correlated with accuracy in the mixed block of the DCCS task. Previous research has found that children who successfully switched in the DCCS task were more likely to sustain their attention in the DP task when compared to children who perseverated in the DCCS (Benitez et al., 2017). Therefore, a negative correlation between Color DP task accuracy and DCCS mixed block accuracy does not replicate previous findings. Perhaps, the large battery of tasks performed caused children to engage in unique strategies across tasks. All of the tasks involve shapes and colors, and it is likely that children used similar strategies across tasks, despite each task needing its own separate strategy.

Theories of Dimensional Attention

There are many accounts related to dimensional attention, and each offer a partial explanation for explicit dimensional attention, but the DNF theory offers the most complete picture of the processes behind dimensional attention. For example, the Cognitive Complexity and Control (CCC) theory suggests that successful performance

and rule-switching in the DCCS arises from a conscious reflection of the rules of the task and that children fail the DCCS when they fail to represent complex rules (Frye et al., 1995; Zelazo, 2004). The CCC theory does suggest that representation of rules is guided by linguistically thinking about the rules of the task. However, language itself is not involved in the developmental changes in rule-representation in the CCC theory. Not only this, but the CCC theory lacks an explanation to the neurological processes behind dimensional attention.

Another theory by Kirkham et al. (2003) called the Attentional Inertia hypothesis suggests that perseveration in the DCCS is due to inflexible attention. Specifically, children have difficulty switching when they fail to inhibit their attention to a feature dimension to free up attention to switch and shift to a different dimension. However, the Attentional Inertia hypothesis does not include a role for labels to influence children's ability to flexibly attend to different dimensions. In general, the Attentional Inertial hypothesis lacks a clear definition of attention, and does not address what mechanisms of attention are involved throughout development.

Additionally, another theory uses a connectionist model that implements an abstract rule representation system (Morton & Munakata, 2002). In this model, perseveration occurs when a latent memory representation forms a bias over an active memory. To successfully switch in the DCCS, the model must more strongly engage the prefrontal cortex representations of dimension (Morton & Munakata, 2002). Here, however, the model is centered on abstract representations of dimension as opposed to label-based representation of dimensions. Moreover, the model focuses exclusively on

the prefrontal cortex and does not specify a role for posterior brain regions in rule-representation or rule-use.

The DNF model proposed by Buss and Spencer (2014) shows how dimensional label learning influences dimensional attention. In this model, the strength between dimensional label representations and object representations influences successful performance in the DCCS. This implies that dimensional label learning can directly impact dimensional attention performance. In the current study, high and low dimensional attention performers had different neural markers during the DLL tasks. DLL is a process that changes in response to experiences. We have evidence that neurologically, children are engaged differently during the DLL tasks in a way that is meaningfully related to their performance on dimensional attention tasks.

In the current study further supports the DNF theory by exemplifying the importance of label learning in dimensional attention performance. The current study shows that there is a frontal and posterior neural network involved in label learning that changes and shifts as children learn labels, improving their ability to attend selectively, flexible, and stably.

Limitations to the Current Study

The current study used a large battery of tasks to assess young children's dimensional attention and dimensional label representations. Although experimenters provided breaks for the participants, completing the entire study in one session was very difficult for the 3- and 4- year-olds to accomplish. In a given session, children sat in a chair while the fNIRS machine was set up and then completed seven total tasks.

Therefore, fatigue may have impacted their ability to complete the tasks correctly and to the best of their ability. Specifically, the DP Color task and DP shape task were either performed as the first task or the last task. To test if fatigue might have affected DP task accuracy scores, a 2 x 2 ANOVA was performed with DP task accuracy and task order. A significant interaction was found between task order and accuracy $F(1,26)=12.131$, $p=0.002$, $\eta_p^2=0.318$. Pairwise comparisons using the Bonferroni adjustment found that children performed better on the DP Color task if it was performed first ($M=0.906$, $SD=0.065$) compared to last ($M=0.633$, $SD=0.075$), $p=.011$. Additionally, children performed better on the DP Shape task if it was performed first ($M=0.792$, $SD=0.085$) compared to last ($M=0.544$, $SD=0.073$), $p=0.036$. This suggests that overall DP accuracy suffered due to task order. A similar test was performed with DCCS accuracy (second or sixth task) and TC accuracy (second or sixth task) and task order, however no significant interaction was found between accuracy and task order. This shows that the DCCS and TC accuracy did not differ as a function of task order. Nevertheless, it is recommended that the tasks be split up over two sessions so that the participants can accomplish the tasks without becoming bored or fatigued in future research.

Further, the current study did not analyze age difference as a factor for performance in the tasks. A future study with a higher sample will be necessary to test between-subject effects of age to understand the developmental shifts in the DLL tasks and dimensional attention tasks.

Future Directions

In the current study, there was not much variability in DLL task performance such that most children performed at ceiling for the Production and Comprehension tasks. It may be interesting to look at the color DLL tasks in a younger population to capture a potential developmental shift in Production and Comprehension and see how that effects dimensional attention tasks. Further, a more complicated DLL task involving shape labels may provide higher variability in performance in 3- to 4-year-olds that may yield interesting developmental differences in how DLL performance predicts dimensional attention performance. Along the same lines, if both color DLL tasks and shape DLL tasks are performed, it may shed light onto how an understanding of both types of labels effects performance in TC Color trials, TC Shape trials, the DP Color task, and the DP Shape task and the DCCS. For example, children who better understand color and shape labels may more easily switch sorting from shape to color and color to shape in the DCCS than children who only fully understand color labels.

Conclusion

The current study sought to better understand the neural dynamics of dimensional label learning in children, and how that might influence children's ability to attend to visual dimensions. We found that children who are successful in dimensional attention tasks show different neural markers in the dimensional label learning task when compared to children who performed poorly in the dimensional attention task. These findings show that label learning does have an influence on dimensional attention. Further research is needed to better understand the developmental shifts of label learning and their implications on dimensional attention performance.

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